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Various methods of circular interpolation performance analysis

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Abstract. The paper discusses the possibilities and methodology of utilizing software, designed to be used with a double ball bar device to analyze CNC machine tool positioning performance, to analyze measurements measured by a different method. The Renishaw Ballbar system is a special tool designed to allow rapid and highly effective checks of positioning performance of any numerically controlled cartesian structure, such as a CNC machine tool, and at the same time allows monitoring its condition and to some extent predict its future development. The system uses sophisticated algorithms to decompose the overall measured inaccuracy of examined machine to values of individual errors and offers possible actions to remove such errors. The ability to push different measurements of circularity, such as measurement of circularity of machined surface on a coordinate measuring machine, would allow checking the presence of various errors without the necessity to measure with a double ball bar device. Therefore, the paper presents the custom software, that shows such possibilities, which was developed at the Department of Automation and Production Systems, Faculty of Mechanical Engineering, University of Zilina.

1 Introduction

CNC machine tools became one of the main means of production across the industry. Therefore the reliability of such an important part of production processes is of high interest. The reliability and overall technical condition of the machine tools and similar devices are usually very closely tied to its so-called precision that usually combines terms such as positioning precision, accuracy, and repeatability of positioning. Maintaining machine tool conditions sufficient for production in required quality calls for adequate maintenance. Effective maintenance requires knowledge of the current condition of the examined machine tool. Such information can be obtained from various sources such as machine tool operators, monitoring of production parameters, or as a result of technical diagnostics.

People usually tend to think of CNC machine tools as of pinnacle of precision that produces errorless parts. However, this is far from true. All machines with moving components inherit some errors that affect positioning performance and thus the precision of produced parts. The deformations, inaccuracies, and errors in the shape and size of produced parts result mostly from the overall state of the machine tool. Machine tool precision is characterized by the ability to produce parts of the required shape and size keeping the required tolerances and at the same time achieving the desired surface roughness. Therefore, the precision, among other factors, can be used as an indicator of the technical state of the machine tool [1].

There are various direct and indirect methods to measure and evaluate the technical state of a device according to its positioning performance. This set of diagnostic methods is specific for machine tools, industrial robots,3D printers, and CNC controlled machines in general. The positioning performance or positioning precision of the machine tool is determined mainly by drives, spindles, slides, and their relative position during machining. Overall machine tool precision is a function of precision of its individual mechanical parts, the performance of its drives, functions of its control system, and of course it is also affected by environmental factors. The machining precision is furthermore affected by various uncertainties and variations arising in the carrier system of the machine such as elastic and thermal deformation of the machine tool body, the contact deformation in moving and static parts, in individual drives, control system, measuring system, tool and workpiece itself [1,2].

2 Measurements of circular interpolation

Some methods of machine tool diagnostics are described in ISO 230 set of standards that consist of ten parts with the common title. Test code for machine tools". These standards describe various methods and devices for machine tool diagnostics, the requirements for the environment, and other important stuff.

One of the most effective groups of diagnostic methods that evaluatethe positioning performance of CNC machines utilizes analysis of the circular interpolation by measurement of radius deviations. The standard interpretation of such measurements is a polar graph that shows the measured deviation ofthe radius. This interpretation is essentially the same regardless if it shows the path of the tool or shape of the machined cylindrical or spherical feature.

In Cartesian machines, the circular motion is produced by the combination of movement of individual axes according to sine and cosine function. If the examined device would be in ideal condition, then the actual shape of the diagram would bethe ideal circle with no deviation from the programmed radius. However, in real-life conditions, it is virtually impossible to reach a perfect state. There are plenty of factors that can have a negative impact on machine tool performance. The negative effects can arise from inaccuracies of construction parts and assemblies, uneven distribution of machine tool weight, wear, negative environmental factors, etc. Each of these factors affects the shape of the diagram bya slightly different waythus it can be identified by various mathematical analyses.

This paper deals with direct and indirect methods to measure positioning accuracy during circular interpolation. The direct methods are used for measurement of the positioning on the examined machine, the indirect method utilizes the measurement of the size and shape of the cylindrical feature of the workpiece machined on such a machine. Direct measuring of positioning accuracy during circular interpolation is performed without the impact of forces that resulting from the machining process. The measurement done on an unloaded machine tool removes the impact of such forces. By contrast, the measurement of machined components must take into account other factors, such as type of tool, cutting conditions, the impact of material, impact of clamping, size of measuring contact, etc. [2,3].

2.1 CNC machine tool diagnostics based on positioning performance during circular interpolation

The device type developed especially for this type of measurementis described in standard ISO 230.4. Such a device is called Ballbar and it utilizes analysis of radii deviations during circular interpolation to measure and evaluate positioning precision, and to identify faults and errors present on the examined device. It is a diagnostic method based on the direct measurement of the machine tool wihout load [2,3].

Fig. 1. Renishaw Ballbar QC20-W.

The Renishaw Ballbar systemis designed to perform a simple, rapid check of a CNC machine tool's positioning performance according to various international standards. The main part of the mechanical assembly (see Fig. 1) is a precise linear displacement sensor that measures changes in the distance of two precisely ground steel balls. The balls fit into magnetic bowls with three contact points made of bearing material. Such construction allows easily measure changes in the radius of a circular path [2].
The radius of the measured circle is specified by Ballbar assembled length. Measured deviations are transferred to the computer thru Bluetooth (or via serial port in case of the older models of this device) where measurement is recorded and analyzed. The measurement can be analyzed and evaluated according to various international standards. Renishaw offers to analyze according to its proprietary standard that is optimized to be used by maintenance technicians as it identifies and enumerate individual faults and errors and offers solutions such as maintenance actions. The main output of measurements with the Ballbar type device is the polar graph of radii deviation in both directions. Deformations on such a graph are directly tied to specific errors occurring on the examined machine. The algorithms built into the software analyze the measurement recordings in order to identify such errors and to evaluate their size and impact to overall precision. In the past, this was a task for experienced diagnosticians. Currently, the Ballbar software is able to recognize and evaluate following errors: to recognize following machine tool errors: backlash, cyclic error, lateral play, master-slave changeover, offset change, plot rotation, positional tolerance, radius change, reversal spikes, scaling error, servo mismatch, spiral error, squareness, slick slip, tri-lobe (straightness), and vibrations [2,3,4].

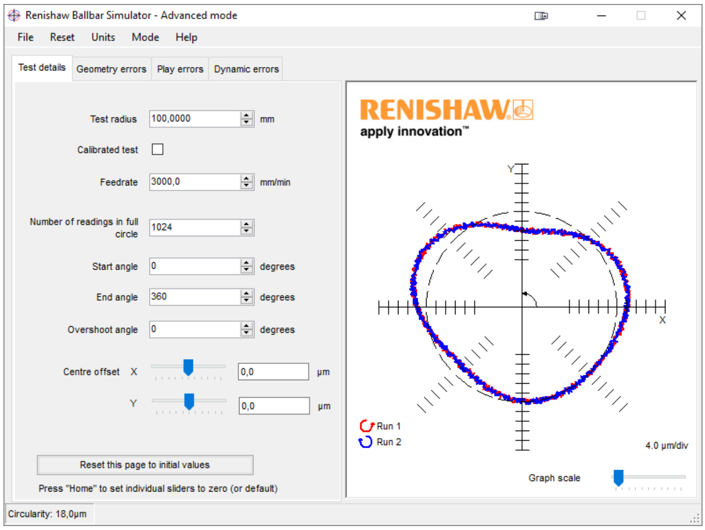

Fig. 2. Renishaw Ballbar Simulator switched to advanced mode.

To increase the level of understanding of operating personnel to measurement outputs, the Renishaw Ballbar system includes software that simulates the impact of various errors onto the shape of the polar diagraphs called the Renishaw Ballbar Simulator (see Fig. 2). This plot simulator saves data, generated according to user-set values of individual errors and faults, in proprietary RTB file which by default contains 512 records of deviation for each measurement directions. The number of readings in a full circle can be changed in advanced mode. The important part is that the RTB files can be read in the standard interface of Renishaw Ballbar 20 software in the section titled Review results, same as records of the real measurements. The only necessary limit is that filter have to be switched from “All reports” to “RTB”.
Even though the Renishaw Ballbar system is meant to be used to measure geometrical errors of conventional Cartesian CNC machine tools, it can be utilized to be used for measurement on a numerically controlled device with virtually any kinematic structure that is capable of circular interpolation or to perform path along multifaceted polygon that does not deviate from circle too much. Still, the software can evaluate errors only on the Cartesian kinematics. Recently, at the Department of Automation and Production Systems Faculty of Mechanical Engineering, University of Zilina, significant effort was put into the utilization of the Ballbar measurement system to be used with industrial robots with serial and parallel kinematics. Similar errors on such machines can have a vastly different effect on the plot shape and its features, therefore the analysis requires a significantly different approach. In order to allow the analysis of the data measured with the Ballbar system, we developed several software tools for converting such measurement records from *.b5r format to other more suitable filetypes such as plain text that can be easily edited and moved between various software as required. This software is mentioned in chapter 2.

2.2 Indirect methods for measurement of circular interpolation

Indirect measurement methods of CNC machine tool precision are based on the measurement of a special so-called master workpiece with features of defined shape and

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size. Such a workpiece is designed with a focus on increasing the visibility of workpiece errors and deformation directly caused by individual machine tool errors. The geometry and deviations of such a workpiece have to be measured by methods of engineering metrology. The contact methods to measure roundness as an indirect method of machine tool diagnostics have their specifics and limitations. First of all, it takes much longer to machine part that can be measured in comparison to direct methods that implements ballbar type device. Also, the time necessary to measure the machined surface must be considered. On the other hand, the machined surface can point out machine tool errors that can not be detected by indirect methods e.g. excessive spindle vibrations [4,6,7].

Machining of a part that can be used for the indirect method of circular interpolation firstly have to be clamped in such a way that prevents the deformation of the workpiece by clamping forces. Deformation due to the clamping forces can introduce deformation of cylindrical shape that would be interpreted as metering error or squareness error.Therefore it is best to avoid clamping to vices and other devices that introduce forces in the direction perpendicular to the plane of machining [6,8].

In our case, the specific shape is a cylindrical hole, the roundness of which was measured by Talyrond 73 (see Fig. 3). This measurement tool is specifically designed to measure the roundness of cylindrical shapes. It uses proprietary software, ROFORM, which is capable of evaluating measurement by spectral analysis and filtering. Data captured by Talyrond are in encoded file *.frm [6].

Fig. 3. Talyrond 73 with a mounted workpiece (right).

3 Evaluation of measurements

Both, direct and indirect methods, mentioned above, provide the ability to analyze measurements in their own proprietary software. Sometimes it is necessary to analyze both sets of data in the same software. In order to allow such a possibility, it was necessary to create software tools for the export of data to a compatible format. In order to allow such

conversion, several applications were developed at the Department of Automation and Production Systems, Faculty of Mechanical Engineering, University of Zilina [4,9].
As software for analysis both, the direct and the indirect measurement, SigmaRound software was selected. It is a highly interactive software package with various filters and reference circles as applied to software-generated or user-imported data files. This software allows also harmonic (chatter) analysis, outlier detection and removal, partial arc analysis, and more. The free version of the SigmaRound was already replaced by the improved commercial software OmniRound, however, we still use the original free version as it is fully sufficient for our purposes [9,10].
To convert balbar measurements (*.b5r files) to format compatible with analytical software, we developed software tool B5R 2 SIG (see Fig. 4) that is capable of exporting to format *.sig, that is a proprietary format for sigma round software, and to plain text file with *.txt extension. The conversion can be done either with a single file or with a batch of multiple files. The measurement record from the Renishaw Ballbar measuring system contains two circular records for the clockwise and counterclockwise direction of movement. The *.sig file type cane store only one circular pattern, therefore the shapes measured for individual directions are stored in separate files that are distinguished by adding prefixes CW or CCW to the exported filename. The software also displaysa simple polar graph of both paths in currently loaded measurement for fast check of data consistency, the data that are to be saved to the header of the file, and a list of files that are in the current batch for conversion.

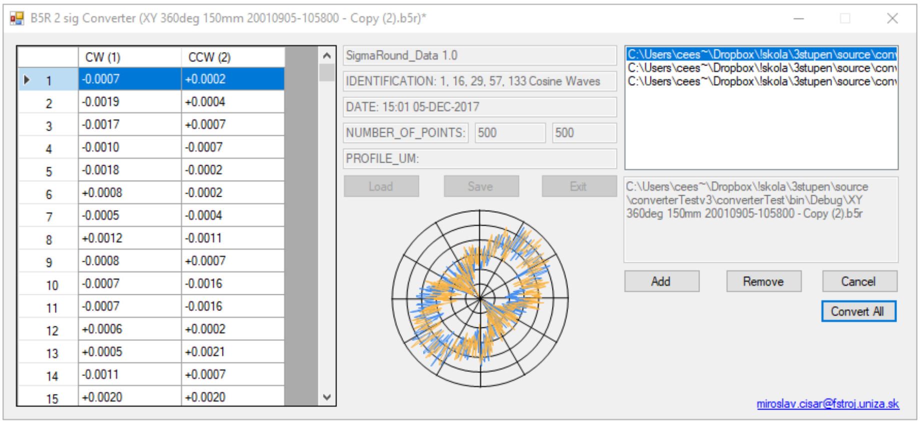

Fig. 4. B5R 2 SIG converter (batch file processing).

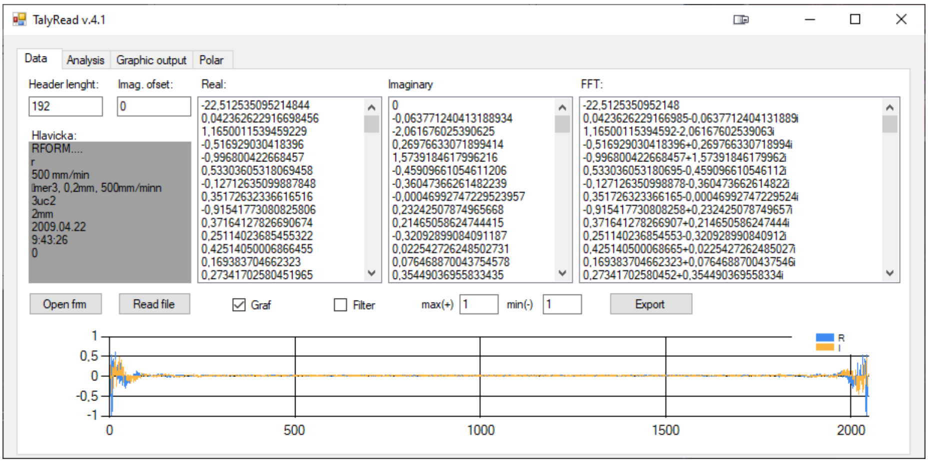

Fig. 5. Taly read with loaded data.

The process of exporting records from ROFORM software is quite more difficult, as the record is stored binary. Furthermore, measurement record does not contain deviations but results of fast Fourier transform, where real and imaginary parts are stored as separate streams. To obtain an actual measured profile, to analyze it externally, it is necessary to read binary recorded value perform inverse fast Fourier transformation. To perform operations necessary for export measurements into the appropriate format the software TalyRead (see Fig. 5) was created. The current version is capable of reading data from *.frm files from ROFORM software, creating such software from other sources, applying basic filters, showing loaded data in the form of size of the real and imaginary part (see bottom of Fig. 5) or as a reconstructed profile in form of polar graph. The charts were added to software mainly to allow verification of data consistency.

Usually, the export to *.xlsx format (Microsoft Excel) is the most useful. Mostly we use Excel to analyze and further process the data and when the algorithms are verified and tuned, then it can be easily implemented in more user friendly and mode effective custom software.

For example, currently, we are testing various ways of feeding data from other software to the Renishaw Ballbar system in order to utilize its internal logic to identify various machine tool errors based on machined part instead of the usage of actual ballbar device for measurement. Import data from other than original Renishaw Ballbar devices to Renishaw Ballbar software is not a trivial task as the results of measurement are stored in an evaluated form so it is not possible to force the system to evaluate profile from *.b5r file. However, simulated profiles generated by the Renishaw Ballbar Simulator (described in chapter 1.1) can be evaluated anytime. Furthermore, the structure of the *.RTB file is quite simpler than the structure of *.b5r file as it contains only a simple header and sequence of radii deviations one record per line. However, files have to contain records for both directions, therefore we are adding reverse direction simply by switching the order of samples as the measurement of circularity of cylindrical shape is not affected by the direction of measurement [4,11].

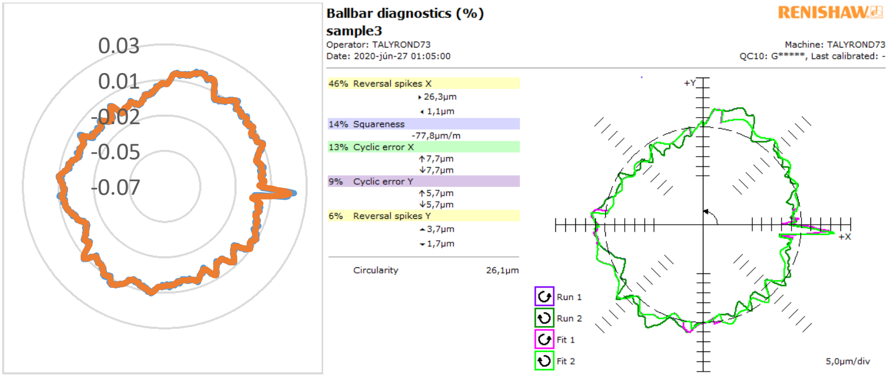

Fig. 6. Profile measured by Talyrond 73 shown in MS Excel (left) and exported to the Renishaw Ballbar system (right).

The record of measurements of deviations of circularity of cylindrical shape, not only from Talyrond 73 but from any device, can be successfully transformed to format readable by Renishaw Ballbar system as shown on Fig 6, where left side shows the polar chart of measured deviations as loaded to Microsoft Excel, the right side shows its evaluation in Renishaw Ballbar system with an evaluation of main machine tool faults. The machine tool faults found by this method are not fully reliable, however if some errors are present in this system of measurement it can point to some problems with machine tool or with the machining process.

4 Conclusions

The development of various methods for the measuring of numerically controlled devices such as CNC machine tools, 3D printers, and industrial robots is still a hot topic. Several highly effective methods are currently applied across the industry, some of which are based on the evaluation of positioning performance during circular motion. Most of these methods offer similar outputs, therefore, it is necessary to allow comparison. This is not always an easy task to implement as the outputs are not always compatible, the data from measurements can be encoded in proprietary formats or even encrypted.

Reliability of production is directly tied to the condition of individual machine tools and its part. Proper maintenance based on a real condition of machinery is therefore essential to keep high reliability. Some of the methods for assessing the machine tool state are compatible enough to analyze data, acquired by one measuring method, by analytical tools of another method. This paper shows an example of direct and indirect methods that deal with the analysis of circular motion or shapes created by circular motion during machining. Data from both direct and indirect methods are usually presented in the form of a polar graph that shows the deviation of the radius. Both types of measurements taken on the same machine tool share similar features and therefore some errors and faults can be diagnosed by both methods.

This paper summarizes some tools, software, approaches, and methods currently used at the Department of Automation and Production Systems, Faculty of Mechanical Engineering, University of Zilina.

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